Lake Simcoe Environmental Management Strategy

Implementation Program

The History of Phosphorus, Sediment and Metal Loadings to Lake Simcoe from Lake Sediment Records

Technical Report: Imp. B.7

1992

THE HISTORY OF PHOSPHORUS, SEDIMENT AND METALS LOADING TO LAKE SIMCOE AS INFERRED FROM LAKE SEDIMENT RECORDS

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The Lake Simcoe Environmental
Management Strategy Technical Committee
December, 1989

LSEMS Implementation Tech. Rep. No Imp. B.7

reprinted from

Water Air Soil Pollut. 39: 337-354
and
J. Great Lakes Res. 15: 265-282

LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

FOREWORD

This report is one of a series of technical reports prepared in the course of the Lake Simcoe Environmental Management Strategy (LSEMS) Implementation Program. This program is under the direction of the LSEMS Steering Committee, comprised of representatives of the following agencies:

- Ministry of Agriculture, Food and Rural Affairs;
- Ministry of the Environment and Energy;
- Ministry of Natural Resources; and
- Lake Simcoe Region Conservation Authority.

The Lake Simcoe Environmental Management Strategy (LSEMS) studies were initiated in 1981 in response to concern over the loss of a coldwater fishery in Lake Simcoe. The studies concluded that increased urban growth and poor agricultural practices within the drainage basin were filling the lake with excess nutrients. These nutrients promote increased weed growth in the lake with the end result being a decrease in the water's oxygen supply. The "Final Report and Recommendations of the Steering Committee" was released in 1985. The report recommended that a phosphorus control strategy be designed to reduce phosphorus inputs from rural and urban sources. In 1990 the Lake Simcoe Region Conservation Authority was named lead agency to coordinate the LSEMS Implementation Program, a five year plan to improve the water quality of Lake Simcoe. The Conservation Authority will have overall coordination responsibilities as outlined in the LSEMS Cabinet Submission and subsequent agreement (Recommendation E.1). At the completion of the five year plan (1994) a report will be submitted to the Cabinet. This report will outline the activities and progress of the LSEMS Implementation Program during its five years. After reviewing the progress of the program the Cabinet may continue the implementation program.

The goal of the LSEMS Implementation Program is to improve the water quality and natural coldwater fishery of Lake Simcoe by reducing the phosphorus loading to the lake. The LSEMS Implementation Program will initiate remedial measures and control options designed to reduce phosphorus inputs entering Lake Simcoe, monitor the effectiveness of these remedial measures and controls and evaluate the overall response of the lake to this program. Through cost sharing programs, environmental awareness of the public and further studies, the goal of restoring a naturally reproducing coldwater fishery in Lake Simcoe by improving water quality can be reached.

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The material presented in these reports is analytical support information and does not necessarily constitute policy or approved management priorities of the Province or the Conservation Authority and/or the evaluation of the data and findings, should not be based solely on this specific report. Instead they should be analyzed in light of other reports produced within the comprehensive framework of this environmental management strategy and the implementation of the recommendations.

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TEMPORAL AND SPATIAL TRENDS IN METAL LOADS TO SEDIMENTS OF LAKE SIMCOE, ONTARIO

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(Received December 2, 1987; revised April 18, 1988)

Abstract. Metal loads to sediments of Lake Simcoe were partitioned into three components, which were attributable to natural background, accelerated erosion, and point + atmospheric sources. These loads were calculated over time using metal concentration profiles together with pre-settlement sedimentation rates based on sonar and time-variable sedimentation rates based on ^{210}Po profiles in cores. Concentrations of metals significantly higher than pre-settlement concentrations were observed in all cores in the case of Pb, back to 80 yr BP on average, and in at least 75% of cores, back to 60 yr BP for Cd and Zn and 30 to 45 yr BP for Cu, Ni, and Cr. Total metal loads increased 3 x for Cu and Ni, 4 x for Zn and Cr, 11 x for Cd and nearly 20 x for Pb from pre-1800 to 0 to 10 yr BP. At present about 90% of the anthropogenic loads of Pb and Cd, and 60 to 70% of the anthropogenic Cu, Ni, Zn, and Cr, are from point + atmospheric sources, the balance being from increased erosion. The direct atmospheric input of Cd is relatively high, approximately 77% of point + atmospheric inputs, while inputs of Cr and Ni are low at 1% and 9%, and inputs of Cu, Zn, and Pb are intermediate at 20 to 40% of point + atmospheric inputs. Two significant findings on spatial distribution of metals were the large increases in metal loads to Cook's Bay following the drainage of 33 km^2 of marshes for agricultural use and the widespread dispersal of Cr from point source(s) in Kempenfelt Bay.

Introduction

Anthropogenic and natural loads of metals to lake sediments have been quantified and differentiated for many lakes using vertical profiles of metal concentrations in combination with sedimentation rates (e.g., Kemp and Thomas, 1976; Kemp *et al.,* 1978; Galloway and Likens, 1979; Evans and Dillon, 1982; Johnson *et al.,* 1986; Johnson, 1987). Variability of sedimentation in time and space may be considerable in many lakes (Evans and Rigler, 1980). Therefore, two problems which may inhibit obtaining good estimates of metal loads to lake sediments are, firstly, oversimplification of temporal patterns in Mass Sedimentation Rate (MSR) and, secondly, an inadequate number of cores where considerable spatial variability occurs.

Temporal variability in MSR may be low in lakes in undisturbed basins and lakes where natural sources of sediment, like lakeshore erosion, are exceedingly dominant. However, Lake Simcoe had considerable temporal variation in MSR. This was predicted initially by an upland soil-loss model (Wilson, 1986) and subsequently substantiated by sediment studies, in which temporal variability in sedimentation was determined by measuring pre-1800 MSR using sonar and time-variable MSRs with the ^{210}Pb method. The three components of total metal loading which may be obtained using sonar MSR and time-variable ^{210}Pb—MSR are background, anthropogenic non-point source due to accelerated erosion, and anthropogenic point + atmospheric detected as excess metal concentration. Many previous studies have not considered accelerated erosion because of the lack of estimates of presettlement MSR.

Spatial variability in MSR has been related to lake depth (Evans and Rigler, 1980), currents (Edgington and Robbins, 1976), underwater topography and physiography (Sly and Prior, 1984) and sizes of sources and sinks at and beyond the lake boundary, like the Holland River marshes of Lake Simcoe which existed until the 1930s (Johnson and Nicholls, 1988). We used a combination of sonar and core MSR measurements to deal with spatial variability in Lake Simcoe. Frequent sonar measurements of the thickness of post-glacial beds provided an accurate estimate of pre-settlement sediment and metal loads, which were then scaled up to obtain post-settlement loads at selected intervals.

The aspects of metal loads to sediments of Lake Simcoe considered in this report are the differences among metals in the relative magnitude of loads from anthropogenic sources, particularly the point + atmospheric loads, their spatial distribution at present compared with that prior to settlement, and temporal patterns generally.

2. Study Area

Lake Simcoe, with an area of 725 km^2 is part of the Trent-Severn Canal System connecting waters of Lake Ontario and Georgian Bay. It is the largest lake in southern Ontario excluding the St. Lawrence Great Lakes. It is a dimictic, hardwater lake with maximum and mean depths of 44 and 16 m, respectively, and a flushing time of approximately 13 yr. The modern sedimentation basin defined by sonar (Johnson and Nicholls, 1988) occupies 319 km^2 (Figure 1). The upper boundary is determined by exposure and slope, being deepest in steep-sloped Kempenfelt Bay (21 to 28 m), intermediate in Cook's Bay (11 to 18 m) and the Main basin (16 to 18 m) and shallowest in the Outlet basin (7 to 13 m). An area of 30 km^2 of sediments east of Georgina Island (Figure 1) was heavy proglacial clays with thin lag deposits at 7 to 11 m (Johnson and Nicholls, 1988).

Most of the major rivers in the 2840 km^2 watershed rise in the interlobate moraine south of Lake Simcoe and drain northward through clay plains, drumlin fields and large areas of organic soils. Approximately 1740 km^2 are occupied by conventional fanning operations. The largest area of organic soils along the lower Holland River was dyked and drained in the 1930s as a series of polders occupying 33 km^2. Before that time the Holland River meandered through the large marsh but the flow is now diverted to the lower Holland River through canals.

The Lake Simcoe basin has a permanent population of 190,000 persons plus 40,000 to 50,000 occupants of cottages during peak-use periods. Approximately 65 km^2 are urbanized, mostly in Orillia, Barrie, Bradford, Uxbridge, Aurora, and Newmarket. After mid-1984 sewage from Aurora and Newmarket was diverted southward via the York—Durham trunk sewer to the Duffin Water Pollution Control Plant on Lake Ontario. Now there are 13 sewage treatment plants which discharge to Lake Simcoe and its tributaries.

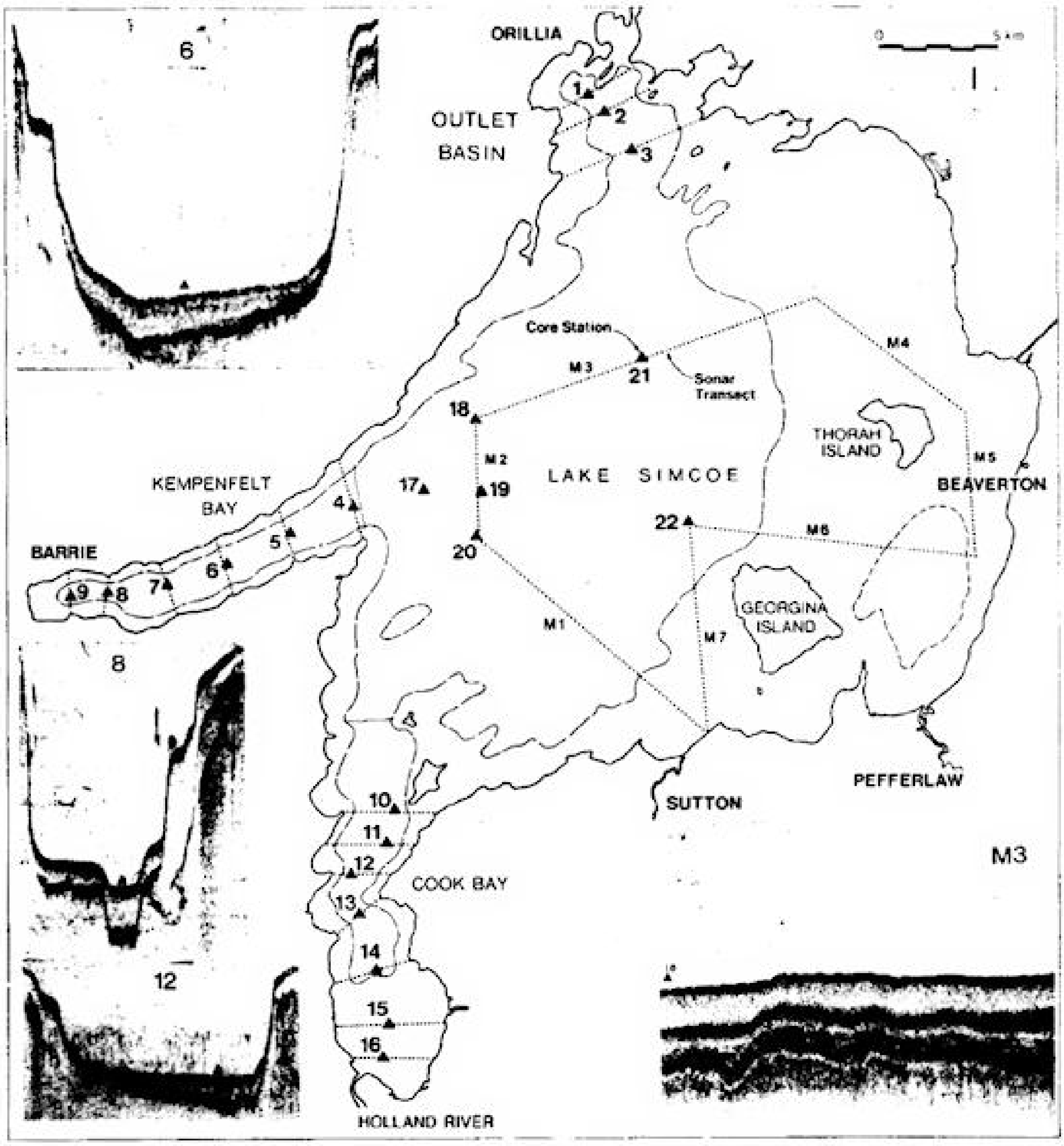


Fig. 1. Map of Lake Simcoe showing sonar transects (dotted lines), the boundaries of the sedimentation zone and proglacial beds east of Georgina Island (dashed lines) and the core stations, numbered 1-22. Core stations 15 and 16 were found to be outside the zone of mineral sediment accumulation.

Recreational use of Lake Simcoe is intense. There are approximately 12000 cottages and 35 marinas; 70% of cottagers own or rent boats. The winter and summer sports fisheries consist of up to 0.5 and 0.25 x 10^6 angler-hours, respectively. There are occasional taste-odor problems in lake water used by some cottagers and smaller municipalities. Recurring, conspicuous blooms of *Anabaena* spp. and other blue-green algae occurred by the early 1970s. Much of the concern about eutrophication of Lake Simcoe is focused on the decline of native lake whitefish *(Coregonus clupeaformis)* and lake *trout (Salvelinus namaycush),* but other factors probably affected indigenous stocks such as heavy harvesting and the invasion of Lake Simcoe by smelt *(Osmerus mordax)* (Evans and Waring, 1987). Cold-water fisheries are currently supported by hatchery-produced stocks. Health advisories have been issued to limit consumption of larger walleye *(Stizostedion vitreum),* largemouth bass *(Micropterus salmoides)* and smallmouth bass *(Micropterus dolomieu)* because of levels of Hg which are > 0.5 mg kg^{-1}. Limnological data on Lake Simcoe are provided by MacCrimmon and Skobe (1970), Ontario Ministry of Environment (1975 and 1982), Nicholls (1976), and Nicholls *et al.* (1985).

3. Methods

Electro-acoustic profiles of bottom sediments were obtained on transects which totaled 117 km (Figure 1) with a 25 kHz Kelvin Hughes Model MS39F sonar. The extent of the deposition zone and depth of modern sediments over proglacial clays of Lake Algonquin were determined from sonar-chart records. Post-glacial sedimentation has occurred through 11,000 yr (Karrow *et al.,* 1975).

Sediment cores were collected at 22 stations on these transects using a KB corer modified to accept Benthos-corer tubes of 6.6 cm diameter. Cores were split at 1-cm intervals to 10 cm, 2-cm intervals to 20 cm and 1 to 5 cm intervals below 20 cm depending on core depth. Our core extruder discarded the outer 0.8 cm of sediment to eliminate effects of smearing along the core tube surface. Sediment was freeze dried and analyzed for ^{210}Po by Flett Research Ltd. in Winnipeg, Manitoba, using the procedure of Eakins and Morrison (1978). Greater precision is achieved by counting ^{210}Po which is in secular equilibrium with ^{210}Pb and has considerably lower background noise. Analysis of Cu, Ni, Zn, Pb, Cd, Cr, Al, and Ca was carried out by Diagnostic Research Laboratories in Toronto. Heavy metals were measured by plasma emission spectrometry following digestion of 1-g samples in nitric perchloric—nitric hydrofluoric acid mix. Calcium was measured by X-ray fluorescence in a tetraborate oxidizing flux. Bulk density, loss on ignition at 600°C and texture were done in our laboratories.

Mean post-glacial MSRs for each of the four basins (Kempenfelt, Outlet, Cook's, and Main basins in Figure 1) were calculated from the mean depth of modern sediment beds measured at equal intervals along sonar transects and the mean bulk density obtained in the deepest slices of the cores in each basin. Bulk density did not increase much below 15 cm in cores. Bulk density in the deepest slices should approximate that of the average in post-glacial beds. Differences occurred among basins and among transects in the Outlet basin. We used values of 0.265, 0.273, and 0.348 g cm^{-3} for the Kempenfelt, Main and Cook's basins, respectively, and 0.38 to 1.24 for Outlet basin transects. There was no apparent rationale for weighting means of sediment depth in any way. There was no observable pattern in thickness of modern beds throughout the Main basin, and, while bed thickness often increased toward the longitudinal center-line of Kempenfelt and Cook's Bays, this trend was often irregular. Post glacial sedimentation (t yr^{-1}) to each basin and the total to the whole deposition zone of Lake Simcoe were calculated. Pre-settlement sedimentation was considered to be virtually the same as post-glacial sedimentation.

Sedimentation over the past 100 yr approximately was calculated using core samples from 20 of the 22 stations; stations 15 and 16 were not within the zone of mineral sediment accumulation. MSRs were calculated from ^{210}Po profiles in two ways, firstly as linear regressions of $\log_e$ ^{210}Po activity on cumulative sediment mass with depth, which gave a time-integrated or mean rate over 100 ± 14 yr BP, and secondly as a time-variable series of MSRs based on ^{210}Po activities and cumulative mass in adjacent core slices.

Metal loads to sediments of the deposition zone were calculated using methods which differentiated loads attributable to natural processes, accelerated erosion and point + atmospheric sources, the latter two comprising the anthropogenic load. Natural metal loads prior to settlement (pre-1800) were calculated as the product of the mean post-glacial MSR or sedimentation and metal concentrations in sediments > 180 yr BP in cores from each basin. Metal loads in sediments deposited after settlement were partitioned initially into total erosion loads (natural plus accelerated) and loads from point + atmospheric sources. Erosion loads were calculated as the product of MSR and Al-corrected background metal concentrations. For example, this calculation for Pb concentration in a surface core slice is

$$\text{Al-corrected background } [Pb]_{0\text{-}1\,cm} = [Pb]_{Pre\text{-}1800} \ [Al]_{0\text{-}1\,cm} / [Al]_{Pre\text{-}1800}$$

Excess concentration of metals (the difference between Al-corrected background and total concentration) times MSR equals the point + atmospheric load. Point and atmospheric loads cannot be differentiated, evident by the fact that anthropogenic atmospheric inputs of metals to sediments in remote lakes are detected as excess concentrations over background (Johnson, 1987) just as are point sources. The 'Al-normalization' procedure was recommended by Kemp and Thomas (1976) to facilitate separation of soil metals, which are associated with a relatively constant proportion of Al, from excess metals derived from point + atmospheric sources.

The 'normalization' would be required when temporal changes in other substantial constituents, like sediment organic matter and carbonates, changed the concentration of metals in sediment. Strong correlations between Al and other metal concentrations, and negative correlations between Ca and metals in pre-1800 core slices, substantiated the need for and use of an Al correction. Finally, we estimated metal loads from accelerated erosion as the difference between erosion loads and pre-settlement loads of metals calculated using sonar-based MSRs.

Present metal loads attributable to accelerated erosion and point + atmospheric sources were estimated by scaling up the pre-settlement metal loads to each basin using the mean ratios of accelerated erosion to pre-settlement loads and the mean ratios of point + atmospheric to pre-settlement loads, respectively, at core stations. These present loads correspond to approximately 0 to 10 yr BP, the average time interval represented by 0 to 1 cm in cores.

Present loads calculated in this way should be more accurate than loads derived from data on only 20 cores, because 470 MSRs were calculated with sonar measurements of depth of post-glacial sediment beds. We obtained the temporal trends through the past 100 yr approximately by preparing a matrix of values of MSR, metal concentration including Al, excess metal concentration and derived metal loads in 5-yr increments for each core. A variable amount of interpolation was required in each core between 1800 and the earliest chronological record based on ^{210}Pb. The development of time-variable MSR series for each basin is described and illustrated elsewhere (Johnson and Nicholls, 1988). The time-variable MSR model was preferred for calculation of metal loads because of general agreement with temporal patterns of sedimentation shown by the soil-loss model (Wilson, 1986; Johnson and Nicholls, 1987). We calculated present metal loads using the integrated MSR model, which gives an average rate, to compare differences between methods.

4. Results

4. METAL CONCENTRATIONS

In the Cook's basin Cu, Ni, and Cr concentrations in pre-1800 sediments (Table I) were significantly lower ($P < 0.05$) than in the Main and Kempenfelt Bay basins, while Zn and Pb

TABLE I. Mean metal concentrations (µg g^{-1}) in pre-1800 (P) and surface (S = 0-1 cm = 0-10 yr BP) sediments in cores from the four sedimentation basins in Lake Simcoe. Numbers in parentheses are standard errors of means and *n* is number of cores.

Basin	Cu		Ni		Zn		Pb		Cd		Cr	
		S	P	S	P	S	P	S	P	S	P	S
Outlet	15.3	12.8	24.9	25.0	68.6	89.3	10.5	37.0	0.11	0.47	49.3	43.3
n = 3	(0.7)	(4.3)	(0.7)	(5.7)	(7.7)	(25.4)	(2.4)	(11.7)	(0.01)	(0.18)	(0.8)	(6.9)
Kempenfelt	20.3	45.7	29.3	47.5	87.8	221.7	11.4	115.3	0.34	1.56	45.8	416.7
n = 6	(1.4)	(8.5)	(1.1)	(4.0)	(5.2)	(16.4)	(0.9)	(8.7)	(0.06)	(0.11)	(0.8)	(155.9)
Cook's	13.3	21.2	22.3	29.8	61.5	124.0	7.5	51.2	0.20	0.64	36.7	75.4
n = 5	(0.8)	(0.7)	(1.0)	(1.1)	(3.8)	(4.0)	(0.5)	(1.9)	(0.06)	(0.10)	(1.3)	(3.9)
Main	19.0	25.5	24.9	34.2	73.5	147.8	8.1	82.6	0.22	0.90	51.5	80.7
n = 6	(1.3)	(0.9)	(0.7)	(1.7)	(2.9)	(8.1)	(0.6)	(13.1)	(0.05)	(0.08)	(2.5)	(6.6)
All cores	19.0	28.6	25.6	35.7	74.1	155.3	9.6	77.5	0.24	0.97	45.8	174.6
n = 20	(1.3)	(3.7)	(0.7)	(2.4)	(3.1)	(12.5)	(0.6)	(8.3)	(0.03)	(0.11)	(1.6)	(57.0)
Quotient S/P	1.5		1.4		2.1		8.1		4.0		3.8	

concentrations were significantly lower than in the Kempenfelt Bay basin. The outlet basin had a significantly lower concentration of Cd in pre-1800 sediments than in Kempenfelt Bay. Pre-1800 metal concentrations were not correlated with MSR in the 20 cores (excluding stations 15 and 16 which were outside the mineral-sedimentation zone).

Significant differences among the four basins in metal concentrations in surface sediments were attributable mostly to greater recent enrichment of Kempenfelt Bay sediments. These had higher Zn, Cd, and Cr concentrations than all other basins, and higher Ni and Pb than the Cook's Bay basin but not the Main basin. There were no significant differences among basins in Cu concentrations.

Surface sediments at stations 8 and 9 in Kempenfelt Bay near the city of Barrie had highest concentrations of all metals, with Cr up to 7.4 x the mean for all cores, Cu to 2.8 x and Ni, Zn, Pb, and Cd to about 2 x the general means for 20 cores. Sediments at stations 1 and 2 in the outlet basin had concentrations that were much lower than average probably because these sediments were of coarser texture.

Metal concentration profiles for one core in each basin are shown here (Figure 2) to exemplify the following: innermost Kempenfelt Bay sediment (core 9) is most enriched with all metals, surface sediments are considerably enriched with Zn, Pb, and Cd throughout Lake Simcoe, Cr enrichment is widespread but is not relatively great in the Outlet basin (core 3), Cu and Ni enrichment is most pronounced in Kempenfelt Bay (core 9) but occurs to a lesser extent in all basins.

Significant enrichment of post-1800 sediment was confirmed when concentrations in core slices exceeded the mean pre-1800 concentration by greater than the t statistic times the standard deviation of the pre-1800 mean (t values for $P < 0.05$ from Snedecor, 1956). This was the case in all 20 cores for Pb, in 19 cores for Zn, 17 for Ni, 16 for Cr and Cd and 15 for Cu. Mean concentrations of all metals except Cd in the Cook's basin, and except Cu in the Kempenfelt basin, were significantly higher in surface sediments (0 to 1 cm and approximately 0 to 10 yr BP) than in pre-1800 sediments. Nonetheless, the Cd concentration in surface sediment in the Cook's basin was 3.2 x that in pre-1800 sediment, compared with a mean of 4.0 x for all 20 cores. In the Kempenfelt basin the mean surface concentration of Cu was proportionately greater than the pre-1800 concentration, than was the surface mean for all cores relative to the pre-1800 mean. Surface sediments in the Outlet basin were less enriched than the rest of the basins with Zn, Pb and Cd and not enriched at all with Cu, Ni, and Cr.

The increase in mean metal concentrations in Lake Simcoe from before settlement to 0 to 10 yr BP was approximately 8 x for Pb, 4 x for Cd and Cr, 2 x for Zn and 1.5 x for Cu and Ni. Variability in metal concentrations among stations also increased from pre-1800 to surface sediments (measured by the change in coefficient of variation in 20 cores) by approximately 2 x for Cu, Ni, Zn, and Pb, and by 9 x for Cr. However, the coefficients of variation of Cd in surface and pre-1800 sediments were similar.

The depths in 17 cores when statistically significant ($P < 0.05$) enrichment occurred were measured in years BP (Table H). Cores from stations 1, 13, and 14 were excluded from this analysis because they showed evidence of bioturbation. Some differences among metals and basins were observed.

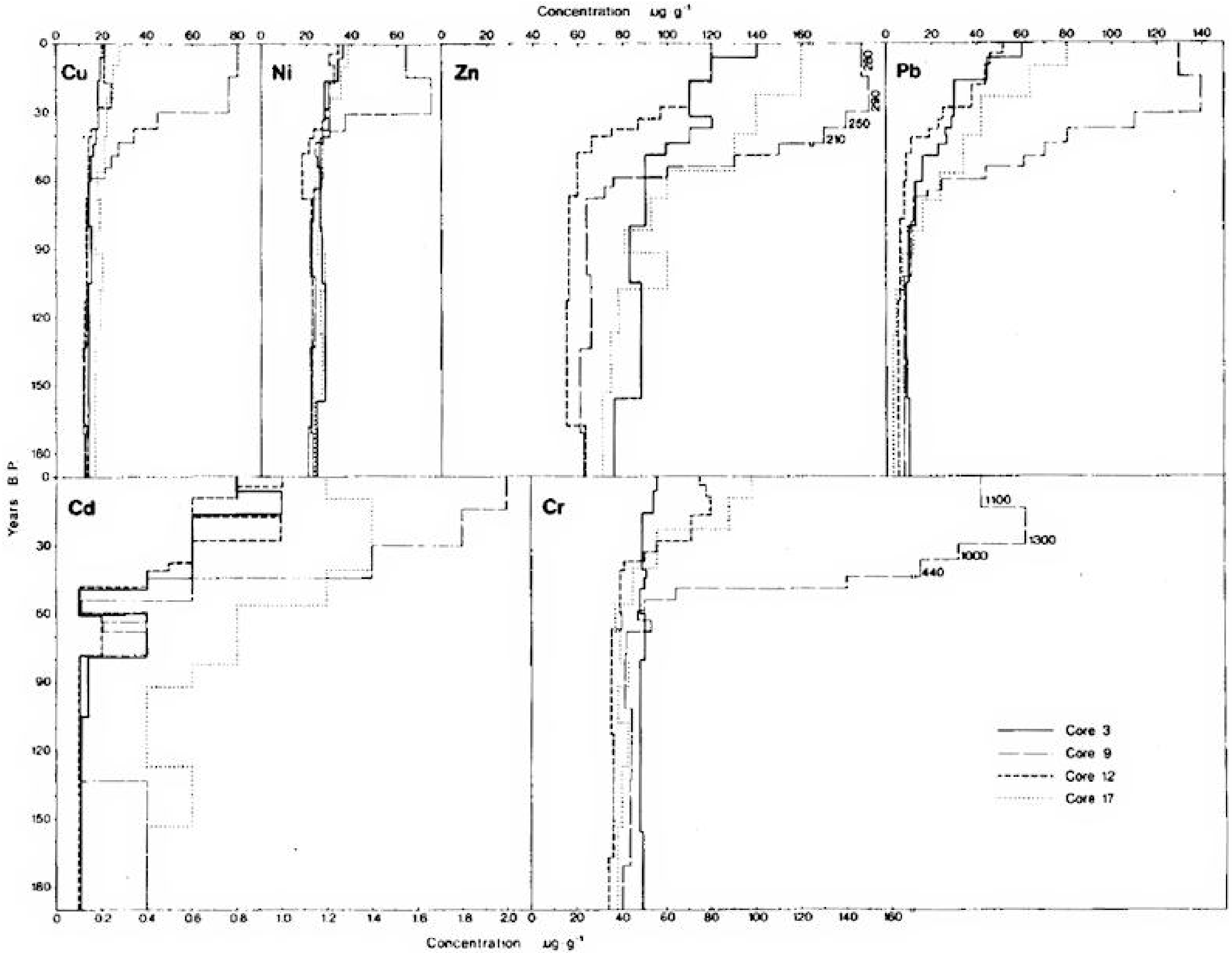


Fig. 2. Concentration profiles of Cu, Ni, Zn, Pb, Cd, and Cr in four sediment cores, one from each basin, plotted against time BP. Core 3 is from the Outlet basin, 9 from the Kempenfelt basin, 12 from the Cook's basin and 17 from the Main basin (see Figure 1).

TABLE II. Earliest detection, in years BP, of statistically significant enrichment in concentration of metals. Numbers in parentheses are standard errors of means and *n* is number of cores.

Basin	Cu	Ni	Zn	Pb	Cd	Cr
Cook's Bay	27.3	22.3	38.3	51.3	42.5	43.3
n - 3	(9.1)	(7.9)	(0.9)	(5.2)	(5.5)	(6.2)
Kempenfelt Bay	43.0	32.2	56.5	76.7	56.2	48.3
n = 6	(11.2)	(6.7)	(4.8)	(7.5)	(3.8)	(3.9)
Main	37.3	32.6	54.8	92.1	57.7	30.9
n = 6	(7.5)	(4.8)	(5.8)	(12.5)	(11.3)	(8.9)
Main + Kempenfelt	40.1	32.3	55.7	84.4	57.0	44.9
n = 12	(4.9)	(3.5)	(3.2)	(8.1)	(8.9)	(2.5)

The period since detection of Pb in the combined Main and Kempenfelt Bay cores was significantly longer than periods for Cu, Ni, Zn, and Cr but not for Cd in these cores. The periods for Zn and Cd were significantly longer than the period for Ni. The periods for all metals except Cr in the Cook's basin were shorter than for periods in the Kempenfelt Bay and Main basins. Differences were significant ($P < 0.05$) only for Zn and Pb in the comparison of the Cook's basin and Main-Kempenfelt basins.

4.2. METAL LOADS

Mean pre-settlement MSRs in the four basins were 15.2 mg cm^{-2} yr^{-1} in the Outlet, 8.2 in Kempenfelt Bay, 7.0 in Cook's Bay and 8.4 in the Main basin (Johnson and Nicholls, 1987). The area-weighted mean MSR for the entire sedimentation basin was 8.6 mg cm^{-2} yr^{-1}. Pre-settlement metal loads in t yr^{-1}. (Table III) were calculated from these MSRs and pre-1800 metal concentrations in cores from each basin.

The distribution of *pre-1800* metal loads was more closely proportional to basin area than to watershed area of each basin. For example, the Cook's basin has 25.5% of the Lake Simcoe watershed but it received only 4.3% (Cu) to 5.6% (Cd) of metal .accumulation. While 61.2% of the watershed drains directly to the main lake, 77.8% (Pb) to 81.8% (Cu) of metals accumulated in the Main basin. The Main basin comprises 81% of the lake's sedimentation basin. The Main and Kempenfelt Bay basins combined received within 3% of expected loads based on their areas. Cook's Bay received considerably less than expected metal loads (0.6 to 0.75 x) based on its basin area. The Outlet basin received much more (1.5 to 2 x) than loads proportional to basin area (Cd excluded), but this was expected because all lakewater exits through it.

The distribution of *recent* (0 to 10 yr BP) loads among basins was much closer to that expected from the areas of their watersheds than were the pre-1800 loads. The Cook's basin received 17.2% (Pb) to 29.4% (Cd) of present loads. The erosion loads (background plus accelerated erosion loads) to the Cook's basin had a narrower range of 18.2% (Pb) to 25.5%

TABLE III. Annual loads (kg yr^{-1}) of metals at 0-1 cm (approximately 0-10 yr BP) for the sedimentation basins of Lake Simcoe partitioned into natural background or pre-settlement (B), accelerated erosion (E) and point + atmospheric (PA) components. Time-variable MSR model was used. These data on E and PA were obtained by scaling up the pre-settlement load B to each basin based on the average ratios in cores in each basin of accelerated erosion to pre-settlement loads and point + atmospheric to pre-settlement loads.

Basin	Basin area km (%)	Cu			Ni			Zn			Pb			Cd			Cr		
		B	E	PA	B	E	PA	B	E	PA	B	E	PA	B	E	PA	B	E	PA
Outlet	13.8 (4.3%)	32	43	15	52	131	20	144	557	98	22	141	209	0.23	1.42	1.35	104	269	12
Kempenfelt	22.5 (7.1%)	38	3	68	54	14	104	162	13	322	20	36	226	0.63	0.10	3.97	83	7	801
Cook's	23.9 (7.5%)	22	167	192	38	290	200	103	786	1301	12	92	692	0.33	2.58	15.39	62	474	746
Main	258.8 (81.1%)	414	124	393	544	163	517	1605	385	3242	181	69	2932	4.66	1.58	30.10	1113	334	1369
Sub total	319.0	506	337	668	688	598	841	2014	1741	4693	235	338	4059	5.85	5.68	50.81	1362	1084	2928
Total present load: B load			3.0			3.1			43			19.7			10.7			4.0	
% of anthropogenic load			33.5	66.5		41.6	58.4		27.1	72.9		7.7	92.3		10.1	89.9		27.0	73.0

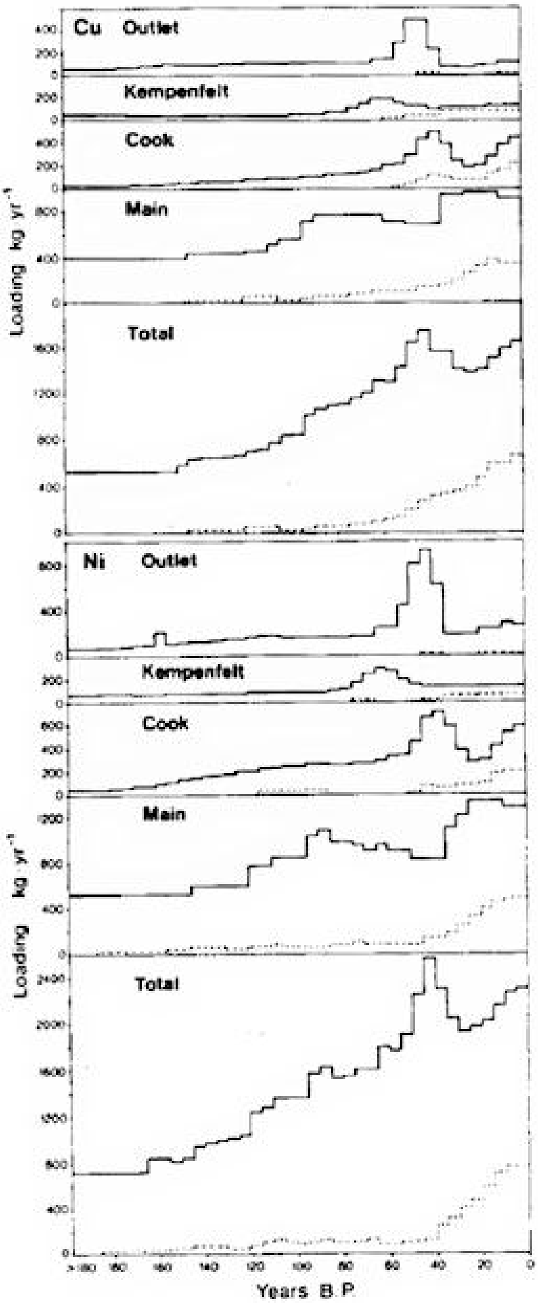
(Ni), but even the percentages of loads due to enrichment were nearly proportional to Cook's basin area, 17.0% (Pb) to 30.3% (Cd). The Main basin received 57.6% (Ni) to 68.7% (Pb) of total loads. The Kempenfelt basin had 5.7% (Zn) to 8.1% (Ni) of loads. However, 16.6% of the total load of Cr and 27.4% of Cr due to point + atmospheric sources accumulated in the Kempenfelt basin. Otherwise, loads. throughout the sedimentation basin due to enrichment by point + atmospheric inputs of Cu, Ni, Zn, and Cd were close to proportional to basin area, while Pb was focussed slightly more in the Main basin and less in the Kempenfelt and Cook's basins (Table III).

The relative increase from pre-1800 to present metal loads was greater than the increase in metal concentrations because MSR also increased. Loads increased from 3 x for Cu and Ni, 4 x for Zn and Cr, approximately 11 x for Cd to nearly 20 x for Pb (Table III). Therefore, present anthropogenic loads comprised from 67 to 95% of present total loads. The increase in Pb and Cd was almost all (90 to 92% of the anthropogenic loads) attributable to enrichment of sediment by point + atmospheric loading, while 58 to 73% of anthropogenic loads of the other metals was due to point + atmospheric sources and the balance of anthropogenic loading resulted from increased sedimentation (Table III).

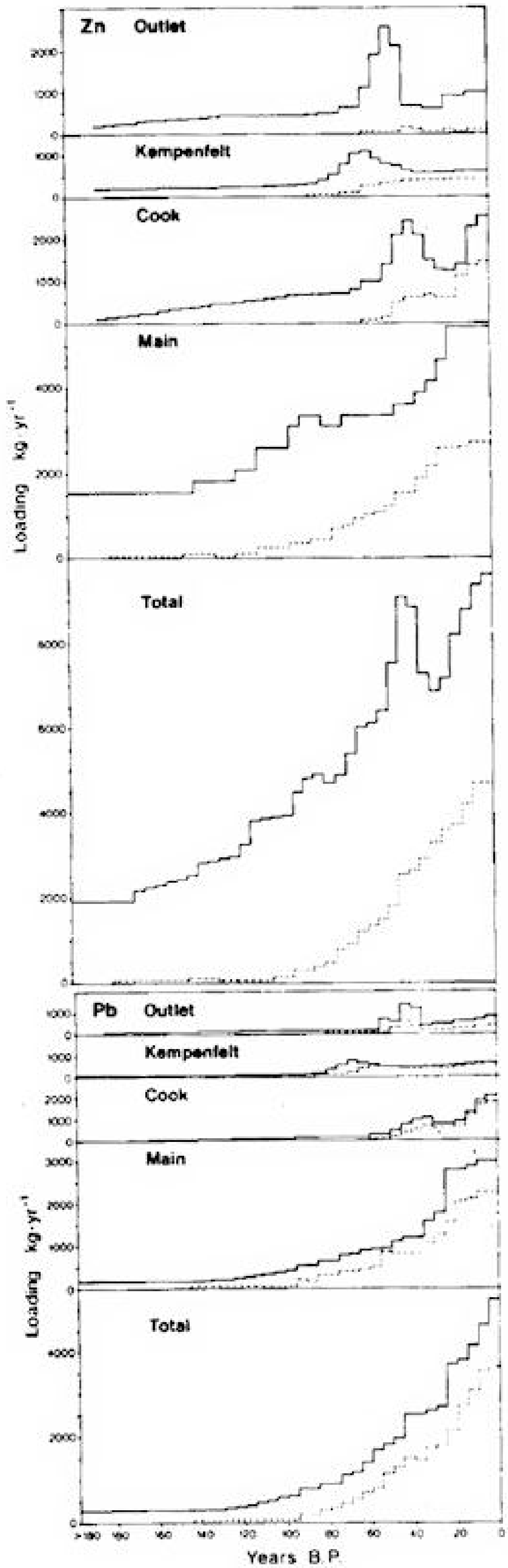
Temporal trends in the total loads of metals (Figure 3) showed differences in rates of change. Total Cu, Ni, and Cd loadings increased almost linearly during the period from 110 to 140 yr BP until 35 to 40 yr BP, then declined and returned at present to approximately the same loading as 35 to 40 yr BP. In contrast total load of Pb continued to accelerate from background to present. Zinc and Cr had accelerating loads, up to about 40 yr BP, which were interrupted by a reduction about 30 yr BP, and then resumed in recent time.

The trend in metal loads due to accelerated erosion followed the sediment accumulation trend, with a rise to about 50 yr BP, a subsequent decline to 30 yr BP and a recent rise to levels characteristic of the period 50 to 100 yr BP. The rise in most metal loads attributable to point + atmospheric inputs was more uniform. For example Cu and Ni point + atmospheric annual loadings increased linearly and by 6 to 7 x during 0 to 50 yr BP, at a rate of about 125 and 150 kg yr^{-1} per decade, respectively. Zinc and Cd increased about 8 x during 0 to 80 yr BP, at a rate of approximately 500 kg yr^{-1} of Zn and 4 kg yr^{-1} of Cd each decade. The point + atmospheric annual load of Pb increased by about 250 kg yr^{-1} each decade during 30 to 80 yr BP and by 600 kg yr^{-1} each decade over the period 0 to 30 yr BP. Lead loads accelerated through the 1950s. Chromium showed the opposite pattern to that of Pb. Although point + atmospheric loads of Cr occurred later (50 yr BP) than those of Pb, Cr annual rates increased by 1200 kg yr^{-1} during 30-50 yr BP and slowed to 300 kg yr^{-1} each decade subsequently.

Recent (0 to 10 yr BP) total and point + atmospheric loads determined using the time-variable MSR model were greater (1.12 to 1.19 x) than loads determined with the integrated MSR model for all metals except Cr for which results were similar. Loads due to accelerated erosion were 1.4 to 2.0 x greater using the time-variable MSR model. We have demonstrated that ^{210}Po-integrated MSRs, which are applicable only to the period 0 to 100 yr BP, would overestimate pre-settlement sedimentation by 100% (Johnson and Nicholls, 1987).



Cu
Outlet
Kempenfelt
Cook
Main
Total
Ni
Outlet
Kempenfelt
Cook
Main
Total
Loading kg yr⁻¹
Loading kg · yr⁻¹
Years B.P.



Zn
Outlet
Kempenfelt
Cook
Main
Total
Pb
Outlet
Kempenfelt
Cook
Main
Total
Loading kg · yr⁻¹
Loading kg · yr⁻¹
Years B.P.

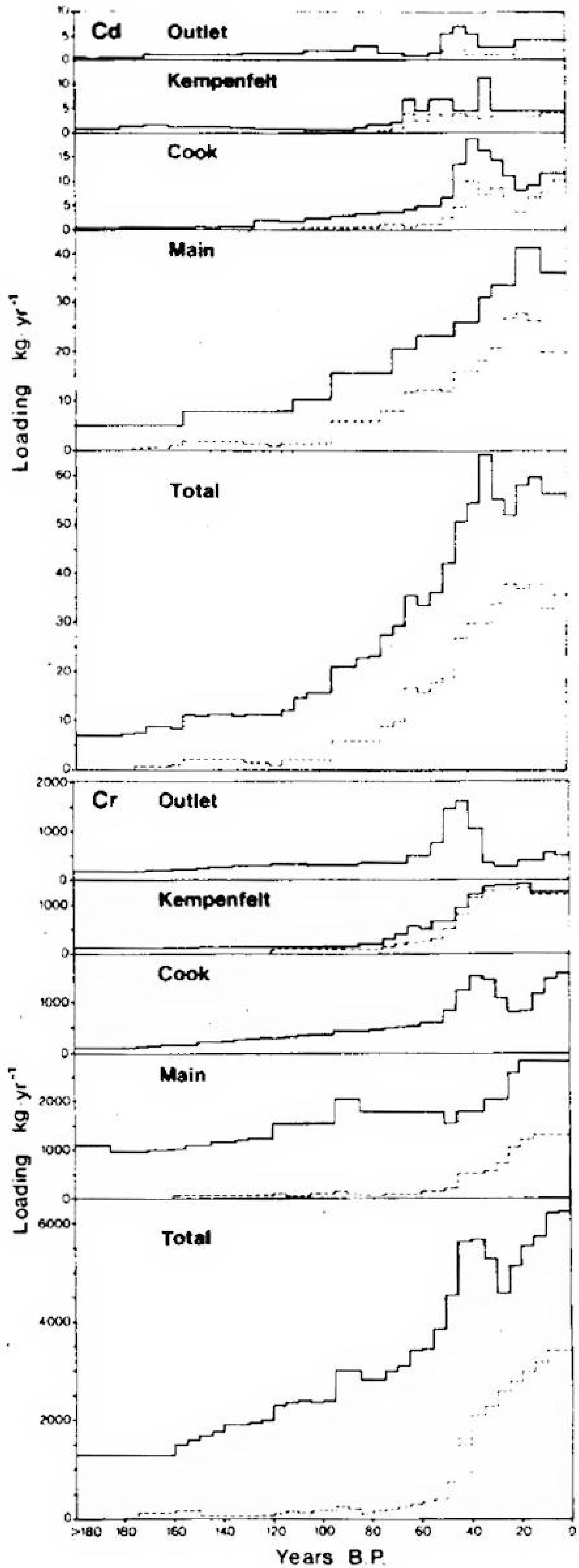


Fig. 3. Loads of Cu, Ni, Zn, Pb, Cd, and Cr from prior to 1800 (pre-settlement) to present. The upper line is total metal load, the lower line is that for point + atmospheric load, and the difference between lines is attributable to erosional load, part of which is the pre-settlement background load (the intercept of total load at > 180 yr BP).

Anthropogenic metal loads due to accelerated erosion would be missed altogether. This is not a relatively large omission for Pb and Cd (Table III), but the loads in accelerated-erosion represent 27 to 42% of anthropogenic loads of Cu, Ni, Zn, and Cr.

5. Discussion

The problem of spatial variability in MSR in Lake Simcoe was overcome by accurately estimating pre-settlement sediment load using sonar measurement of post-glacial sediment depths at many points and scaling-up to later sediment loads using ratios of recent : pre-settlement MSR at coring sites. Similarly, ratios of post-settlement metal loads to pre-settlement loads at core stations were used to scale up accurate estimates of pre-settlement loads. Temporal variability in sedimentation was examined by interpolating within ^{210}Po-sediment mass series. The temporal trends were similar to those of Wilson (1986) who used a soil-loss and delivery model. Estimates of P loads calculated using these sedimentation data together with P concentrations and the P retention coefficient for Lake Simcoe agreed closely with results of P inventory at sources (Johnson and Nicholls, 1987).

However, there are no inventories of metal inputs to Lake Simcoe with the exception of estimates of precipitation loads. Even if inventories existed, no estimates of losses at the outlet of Lake Simcoe were available to allow us to compare these losses plus inputs estimated from metal accumulation in sediments with inventoried inputs as a check on our method. Consequently, our metal loads to sediments underestimate lake loadings but they provide valuable information on temporal changes and spatial differences in metal loads. The sediment record also provides information on the magnitude of anthropogenic loads relative to natural loads and the contributions from point + atmospheric sources may be compared with contributions in accelerated erosion.

Loads of the six metals were significantly greater at present (0 to 10 yr BP) than before settlement. Higher loads resulted partly as a result of the increase in sedimentation from 27 000 to 64,000 *t* yr and partly because of enrichment of sediments. Concentrations of metals significantly higher than pre-settlement concentrations occurred in most cores (all cores for Pb) and, in fact, significantly enriched sediments were observed back to 80 yr BP in the case of Pb, close to 60 yr BP for Zn and Cd and 30 to 45 yr BP for the others. As expected, metals with greater increases in concentration relative to pre-settlement concentrations had detectable enrichment for longer periods.

Anthropogenic loads of all metals to Lake Simcoe sediments at present exceeded pre-settlement loads. The six metals fall into three groups; over 90% of Pb and Cd, about 85% of Zn and Cr and close to 75% of Cu and Ni loads were anthropogenic. Only about 60% of the total present loads of all metals would be anthropogenic if increased sediment input, that is accelerated erosion, was the only factor involved. The percentages of the anthropogenic loads attributable to enrichment by point + atmospheric loads were about 90% in the cases of Pb and Cd, 73% for Zn and Cr and lowest for Cu and Ni, 67 and 58%, respectively.

The temporal increase in point + atmospheric loads of Cu, Ni, Zn, and Cd by constant amounts may represent the balance between industrial expansion at an exponential rate and improving wastewater treatment. There is a suggestion of lower increases in recent time, but this is obvious only in the case of Cr and not at all evident in the case of Pb whose input to sediments was still accelerating. The differences in both temporal and spatial patterns between Pb and Cr loadings probably reflect their main sources, that is a long term acceleration of fuel consumption yielding Pb and more recent emissions of Cr from local industry which apparently reduced losses in the 1950s.

We compared present and pre-settlement concentrations and ratios of loads in Lake Simcoe with Great Lakes sediments and other Ontario lake sediments (Table IV). Lead loads increased by 5 to 6 x in the upper Great Lakes, and 10 to 11 x in the off-system lakes and Lake Erie. The increase in Lake Ontario was only 3 x, but it is likely much higher because the pre-settlement Pb concentration appears to be overestimated by several times. Lead loadings to Lake Simcoe increased by 20 x. If sedimentation had not increased in Lake Simcoe after settlement this ratio for Pb would be 8 x, a value close to those for the other lakes. The temporal trend in sedimentation given by sonar and a ^{210}Po-based MSRs in Lake Simcoe and the sediment output model used by Wilson (1986) both showed large increases in sedimentation after settlement.

Possibly sedimentation in many other lakes where metal loads have been measured did not remain constant over time, particularly those lakes where agricultural and urban land uses were extensive, such as lakes Huron, Erie, and Ontario. The argument for constant sedimentation through time has been based on the dominance of ongoing lakeshore erosion. The International Joint Commission (1978) estimated that shoreline erosion contributed 89% of the total sediment loading to Lake Superior, 97% to Lake Michigan and 63 to 67% to Huron, Erie and Ontario. Accelerated erosion from the watershed is the same order of magnitude as shoreline erosion in these three lakes and it should not be neglected. In fact, tributary inputs may exceed shoreline inputs locally. Therefore, MSRs likely increased substantially after settlement, and the relative increase in loads of many metals probably has been underestimated in Huron, Erie and Ontario.

The present Cd load to Lake Simcoe sediments, although it increased by 11 x since settlement, is similar to pre-settlement loads in Lake Ontario and Lake Erie, although these probably have been overestimated for reasons given earlier. The present Cd load to Lake Simcoe is several times less than present loads to Ontario and Erie and the same magnitude as present loads to the upper Great Lakes. Lake Simcoe had significant enrichment by Cr, primarily via point-source discharges to Kempenfelt Bay over approximately 50 yr. This has not been observed often (see Table IV), but Walters *et al.* (1974) showed enrichment of surface concentrations of Cr in the central and western basins of Lake Erie and in Cleveland and Buffalo harbors, and Nriagu *et al.* (1983) found the same in Hamilton and Toronto harbors. Zinc loads also increased by 4 x in Lake Simcoe sediments, which means that both sedimentation and excess concentration doubled approximately. The lower Great Lakes showed a similar increase, 3 to 6 x , while the upper Great Lakes and off-system lakes changed by approximately 2 x Loads of Cu and Ni to Lake Simcoe increased by 3 x , which is primarily the result of accelerated (2.4x)

TABLE IV. Comparison of average pre-settlement (P) and present, surface (S) metal concentrations in cores from the Great Lakes and 14 off-system lakes in Ontario. Average MSRs and the number of cores *(n)* are given, including both average pre-settlement and present MSRs for Lake Simcoe.

Lake(s)		Average MSR (mg cu yr)	Cu		Ni		Zn		Pb		Cd		Cr		Source of data
			P	S	P	S	P	S	P	S	P	S	P	S	
Simcoe	20	8.6/44.8	19.0	28.6	25.6	35.7	74.1	155.3	9.6	77.5	0.24	0.97	45.8	174.6	Present study
Superior	6	37.8	54.2	153.3	50.8	52.3	95.2	169.7	19.3	111.6	0.68	2.48	44.1	44.9	Kemp *et al.* 1978
Georgian Bay	20	13.8	313	56.7	45.8	96.7	111.2	222.4	12.4	66.9	0.65	1.57	79.9	82.9	Johnson, 1983: Kemp *et al* 1978
Huron	9	24.4	28.7	58.7	30.8	71.4	68.1	181.3	21.3	118.1	0.74	2.41	36.9	43.1	Robbins. 1980; Kemp *et al*, 1978
Ontario	5	43.6	41.7	96.8	-	-	104.9	486.7	77.4	228.0	0.92	5.28	-	-	Kemp and Thomas, 1976
Erie	13	93.6	35.2	75.4	-	-	94.9	273.8	10.3	106.2	1.08	3.72	-	-	Kemp and Thomas, 1976: Nriagu *et al,* 1979
Off-system	17	9.9	36.4	36.4	19.2	22.2	96.0	152.5	6.1	66.7	0.81	2.02	43.4	45.5	Johnson, 1987

sedimentation. Copper and Ni loads increased by 2 to 3 x in most of the Great Lakes, but no increase in Ni loading was observed in Lake Superior or of either metal in the off-system lakes in Table IV.

The proportions of point + atmospheric metal inputs that are atmospheric, and not subject to control locally, are of interest. Therefore, we compared wet precipitation loads of metals (Ontario Ministry of the Environment, 1983, 1984) at the Coldwater and Uxbridge monitoring stations with the point + atmospheric component of anthropogenic loads to sediments. The direct precipitation load to the whole lake was compared with the accumulation of metal in the sedimentation basin. We appreciate that losses in the outflow, focusing of lake loadings in the sedimentary basin of the lake and other factors complicate the comparison.

Cadmium in the direct precipitation loading to the lake was 77% of our estimate of point + atmospheric load. The atmospheric contribution of Cd probably is very important. In contrast, direct precipitation loads of Ni with 9% and Cr with 1% are probably relatively unimportant in Lake Simcoe. Between these two groups, Cu, Pb, and Zn loads, with 43, 30, and 21%, respectively, of the point + atmospheric loads, likely are significant although perhaps not as important as urban sources (storm drainage, sewage treatment plants and separate industrial effluents). The potentially important contributions of Cd, Pb, and Zn in precipitation were expected but that of Cu was unexpected based on earlier studies (Johnson, 1987).

Two significant findings on spatial distributions of metals of relevance to ecosystem management were the effect of loss of Cook's Bay marshes on metal inputs and the widespread dispersal of Cr from point source(s) in Kempenfelt Bay. Pre-settlement metal loads to Cook's Bay sediments were much less than expected in relation to watershed area, in contrast with present loads. The low loads to Cook's Bay prior to approximately 50 yr BP likely were attributable to high rates of removal by marshes in the lower Holland River. Approximately 75% of the P input to these marshes was retained (Johnson and Nicholls, 1987).

During the interval 40 to 50 yr BP, at the time when the river was dyked and the marshes drained, metal loads to Cook's Bay sediments increased at rates greater than those before or after; Ni, Zn, Cd, and Cr loadings increased by 7 to 10 x, Cu by 4 x, and Pb by about 5 x. In Kempenfelt Bay high Cr in sediments indicated inputs there which were large enough to produce a substantial lakewide increase (4 x) over the pre-settlement loading. During 0 to 10 yr BP 94% of the Cr load was attributable to the point + atmospheric component in sediments in Kempenfelt Bay. Cook's Bay and the Main basin also accumulated considerable anthropogenic Cr. The atmospheric loading was negligible compared with point-source Cr. The concentration of Cr decreased in every direction away from Kempenfelt Bay, including Cook's Bay, suggesting that most Cr was from point-source inputs in Kempenfelt Bay.

Acknowledgments

Glen Robinson (Ontario Ministry of the Environment) and Larry Culp (Department of Fisheries and Oceans) collected the sediment cores and sonar records. Tim Rance, Rod Allan, and Jack Lawrence (Ontario Ministry of Natural Resources) provided a boat and position fixing for running the main-basin transects. Garry Bruce (Environment Canada) helped to collect sonar records in the bays. Larry Culp and Lynda Nakamoto prepared the sediment samples. John Novog of Diagnostic Research Laboratories of Toronto did ICP analyses and Robert Flat of Winnipeg did the ^{210}Po determinations. Peter Sly provided advice on interpretation of sonar records.

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APPENDIX

MEMBERSHIP ON THE STEERING COMMITTEE FOR THE LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

D. Marquis, Lake Simcoe Region Conservation Authority (Chairman)
A. Morton, Lake Simcoe Region Conservation Authority (past member)
J. Barker, Maple District, Ministry of Natural Resources
E. Cavanagh, York County, Ministry of Agriculture and Food
R. DesJardine, Central Region, Ministry of Natural Resources (past member)
J. Kinkead, Watershed Management Branch, Ministry of the Environment (past member)
J. Merritt, Director - Central Region, Ministry of the Environment
P. Miller, Watershed Management Branch, Ministry of the Environment
B. Noels, Lake Simcoe Region Conservation Authority (Secretary)

APPENDIX

MEMBERSHIP ON THE TECHNICAL COMMITTEE FOR THE LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

B. Noels, Lake Simcoe Region Conservation Authority (Chairman)
J. Beaver, Central Region, Ministry of the Environment
R. DesJardine, Central Region, Ministry of Natural Resources (past member)
J. Dobell, Huronia District, Ministry of Natural Resources
D. Green, Resources Management Branch, Ministry of Agriculture and Food (past member)
B. Kemp, Lake Simcoe Region Conservation Authority
J. Kinkead, Watershed Management Section, Ministry of the Environment (past member)
R. MacGregor, Central Region, Ministry of Natural Resources (past member)
N. Moore, Victoria-Haliburton County, Ministry of Agriculture and Food
K. Nicholls, Water Resources Branch, Ministry of the Environment
B. Peterkin, Central Region, Ministry of Natural Resources
T. Rance, Maple District, Ministry of Natural Resources
B. Stone, Northumberland County, Ministry of Agriculture and Food
M. Walters, Lake Simcoe Region Conservation Authority
C. Willox, Lake Simcoe Fisheries Assessment Unit, Ministry of Natural Resources
K. Willson, Watershed Management Section, Ministry of the Environment

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